Theoretical Modeling and Measurement Comparison of Season-long Rice Field Monitoring

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Abstract

The development of a theoretical model to describe the scattering mechanisms involved in the remote sensing of rice crops is essential, as it ensures correct application of remote sensing data for rice monitoring. The theoretical model used in this study is based on the radiative transfer theory applied on a layered dense discrete random medium. The dense medium phase and amplitude correction theory (DM-PACT), which considers the coherent effects of the scatterers, is incorporated in the development of the phase matrices of the scatterers, which are modeled after the physical geometry of the plants. Ground truth measurements of rice fields were acquired at Sungai Burung, Selangor, Malaysia for an entire season. These measurements are used in the theoretical model to calculate the backscattering coefficients of rice fields. The results are then compared to those obtained from RADARSAT images to test the validity of the model. Comparisons show promising results, but further research is required to improve on the current model.

Introduction

In recent years, there has been a lot of international interest in the use of microwave remote sensing for rice field monitoring and yield prediction applications. Initial studies [1-3] have shown that earth observation satellites such as ERS-1 and RADARSAT can be used to classify rice covered areas from non-rice areas due to the high temporal variations in the backscattering coefficient of rice fields. In addition to that, the backscattering information allows the growth stage of the rice plants to be determined. However, the actual interaction between electromagnetic waves and rice crops still remains relatively unknown. There is therefore a need to develop a theoretical model that will enable us to understand the scattering mechanisms involved when electromagnetic waves interact with rice crop canopies. This theoretical model will ensure correct application of remote sensing data, as well as allow the retrieval of physical parameters of rice crops using inversion algorithms.

Ground Truth Measurements

Ground truth measurements of rice fields were obtained at regular 12 day intervals between 27^{th} August 2004 to 1^{st} December 2004 at Sungai Burung, Selangor, Malaysia. These measurements were acquired from 6 different test fields in the region. Parameters that were measured include plant geometry (such as plant height, leaf length, leaf width, leaf thickness and leaf inclination angle), plant density, plant gravimetric water content and plant biomass. These measured parameters were then used to calculate and obtain other parameters for the theoretical model. RADARSAT images were acquired on the 27^{th} of August, 20^{th} of September, 14^{th} of October and 6^{th} of November of 2004, which coincide with four ground truth measurements. The RADARSAT operates at 5.3 GHz (C-Band), and all the images were obtained using Fine Mode 2.

Theoretical Modeling

In this study, the theoretical model is developed based on the radiative transfer theory [4], which describes the change in intensity of an electromagnetic wave due to scattering and absorption as it travels through an inhomogeneous medium, and is given by:

$$\cos\theta \frac{d\bar{I}}{dz} = -\bar{\bar{\kappa}}_e \bar{I} + \int \bar{\bar{P}} \bar{I}\, d\Omega \tag{1}$$

where $\bar{I}$ is the Stokes vector, $\bar{\bar{\kappa}}_e$ and $\bar{\bar{P}}$ are the extinction matrix and phase matrix of the medium respectively. This equation is solved iteratively up to second order in both the upward and downward directions. The phase matrices of the rice canopies are developed using the generalized Rayleigh-Gans approximation to obtain the scattered fields from needle shaped and cylindrical scatterers [5] with Fresnel phase corrections being considered by including the higher order terms in the expression of the scattered fields [6]. The dense medium phase and amplitude correction theory (DM-PACT) [7, 8] has also been incorporated to include the coherent effects of closely packed scatterers, by multiplying an array phase correction factor to the Stokes matrix to obtain the phase matrix of the medium. The phase matrix is thus given by:

$$\overline{\overline{P}}(\theta_s, \phi_s; \theta_i, \phi_i) = <|\psi^2|>_n \cdot \overline{\overline{S}}(\theta_s, \phi_s; \theta_i, \phi_i) \tag{2}$$

where $\overline{\overline{S}}$ is the Stokes matrix and $<|\psi^2|>_n$ is the array phase correction factor given by:

$$<|\psi^2|>_n = \frac{1 - e^{-k_{si}^2\sigma^2}}{d^3} + \frac{e^{-k_{si}^2\sigma^2}}{d^3} \sum_{q-1}^{\infty} \frac{(k_{si}^2\sigma^2)^q}{q!} [(\sqrt{\frac{\pi}{q}}(\frac{l}{d}))^3 exp(\frac{-k_{si}^2 l^2}{4q}) - a(k_x)a(k_y)a(k_z)] \tag{3}$$

where:

$$k_{si} = |\overline{k}_s - \overline{k}_i| \quad and \quad a(k_r) = \sqrt{\frac{\pi}{q}}(\frac{l}{d}) exp(\frac{-k_r^2 l^2}{4q}) Re\{erf(\frac{(qd/l) + jk_r l}{2\sqrt{q}})\}$$

$\overline{k}_i$ and $\overline{k}_s$ are the propagation vectors in the incident and scattering directions, l is the array correlation length, d denotes the average distance between scatterers and σ is the standard deviation of scatterers from their mean positions.

The rice canopy is modeled as either a single layer or multilayer dense discrete random medium, depending on its growth stage, over a smooth water surface. Table 1 shows the different models used for the different growth stages of the rice crops corresponding to its age and dates of RADARSAT image acquisition. In its early vegetative stage, corresponding to the RADARSAT image obtained on the 20^{th} of September, the rice model consists of a single layer of needle-shaped scatterers, in the consideration of the uniform orientation distribution of the rice leaves. For the image obtained on the 14^{th} of October, the rice plants are now in their late vegetative stage, and the canopy is modeled as a double-layer medium. The upper layer consists of needle shaped leaves, while the lower layer is a combination of needle shaped leaves and cylindrical stems. During the reproductive stage, tiny cylinders are added to the upper layer of the model to simulate grains. This corresponds to the RADARSAT image acquired on the 6^{th} of November. The RADARSAT image obtained on the 27^{th} of August will not be included in this study as the seeds have just been broadcasted and the only source of backscattering is the soil. Test fields 2 and 3 have also been omitted due to incomplete data collection as a result of heavy rains and partial destruction of rice fields respectively.

The list of parameters used in the model is shown in Table 2. The water surface is assumed to be flat and smooth. The dielectric constants of water and rice plants are calculated from the equations given in [9]. The standard deviation of scatterers from their mean positions is chosen to be $0.5d$, where d is the average distance

Table 1: Various models used for the different growth stages of rice plants corresponding to plant age and date of RADARSAT image acquisition

Date	Test Field	Age (days)	Growth stage	Model	Scatterers
20/9/04	1	27	early vegetative	single layer	needles
	4	26	early vegetative	single layer	needles
	5	29	early vegetative	single layer	needles
	6	21	early vegetative	single layer	needles
14/10/04	1	51	late vegetative	double layer	needles, stem cylinders
	4	50	late vegetative	double layer	needles, stem cylinders
	5	53	late vegetative	double layer	needles, stem cylinders
	6	45	late vegetative	double layer	needles, stem cylinders
6-11-04	1	75	early reproductive	double layer	needles, stem cylinders,grain cylinders
	4	74	early reproductive	double layer	needles, stem cylinders,grain cylinders
	5	77	early reproductive	double layer	needles, stem cylinders,grain cylinders
	6	69	early reproductive	double layer	needles, stem cylinders,grain cylinders

between the scatterers. The angle distribution parameters for the leaves, stems and grains are based on the equation in [10].

Table 2: Model input parameters

Model Input Parameters	Values
array standard deviation of scatterers	0.5d
array correlation length	1.0d
radius and length of leaves, stems and grains	according to test field measurements
volume fraction of leaves, stems and grains	according to test field measurements
layer heights	according to test field measurements
plant dielectric constant (at 5.3 GHz)	according to test field measurements
leaf, stem and grain angle distribution parameters	according to test field measurements

Results and Comparisons

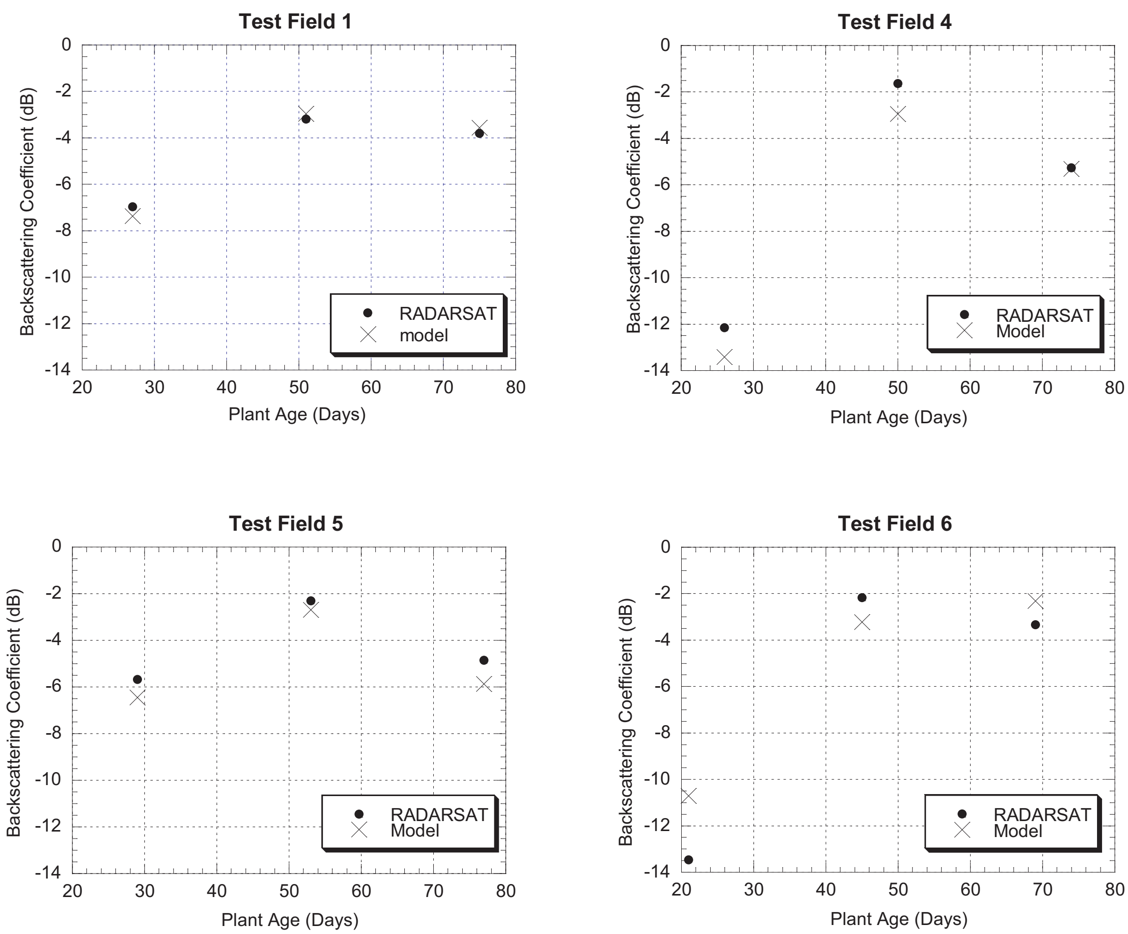

Figure 1: Comparisons of theoretical and measured HH polarized backscattering coefficients of rice canopies for (a) Test Field 1, (b) Test Field 4, (c) Test Field 5 and (d) Test Field 6 at various stages of growth

The theoretical model is used to calculate the HH polarized backscattering coefficient of the rice canopies, at a frequency of 5.3 GHz and at an incident angle of 39 $^{\circ}$ to match that of Fine Mode 2 of RADARSAT. The results for test fields 1, 4, 5 and 6 are compared to the corresponding backscattering coefficients obtained from the RADARSAT images, and are shown in Figure 1. As expected, both results show a large increase in the backscattering coefficient when the crops are about 60 days old, compared to when the crops are 20 days old. This is due to the rapid growth of rice plants in their vegetative stages, thus increasing the canopy height and the volume fraction of scatterers. There is then a slight decrease in the backscattering coefficient as the crops move into the reproductive stage and grains begin to form. This could be due to the decrease in the density of the rice canopy as smaller plants and stems die off. These trends agree with those that have been reported in other studies [2].

Comparisons between the backscattering values obtained from the RADARSAT images with the values calculated using the theoretical model show promising results. Even though there are errors up to approximately 2dB, the majority of the points are quite closely matched. The small differences and errors can be attributed to the fact that the ground truth measurements may not be an ideal representation of the entire test field, but are only approximations. Another reason for the differences is that using needle-shaped scatterers to model leaves may not be accurate enough as it does not describe the actual geometry of rice leaves. Currently, the phase matrix of a medium containing general ellipsoidal and elliptical disk-shaped scatterers is being developed to improve on the current model presented in this paper. This will enable a better representation of the geometry of rice plants in the model. Measurement comparisons will also be carried out at different frequencies, incident angles and polarizations for a more rigorous testing of the model.

Conclusion

In this study, a theoretical model was developed for rice fields based on the radiative transfer theory applied to a layered discrete random medium. The DM-PACT was used to account for the coherent effects of the scatterers. Season-long ground truth measurements were obtained and used as input parameters for the model to calculate the HH backscattering coefficients of rice fields. Results were then compared to those obtained from RADARSAT images. Comparisons show that most of the results are closely matched, while one or two points have errors of about 2dB. This shows promising results for the model, but a phase matrix for general ellipsoidal and elliptical disk-shaped scatterers needs to be developed for a better representation of rice leaves. In future, the model can be tested with measurement results from scatterometer measurement more rigorously to check its validity.

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